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Measure of fracture toughness of compressive fiber failure in composite structures using infrared thermography

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ABSTRACT

Fracture toughness is one of the most important properties of any material for a lot of design applications involving damage and crack growth. Unfortunately, its value can be difficult to evaluate with standard methods such as the "compliance" method. In this work, two special cases have been studied and infrared thermography has been used to overcome the limitations of conventional methods.

Compressive fiber failure in unidirectional composite laminate has been chosen due to its difficulty to evaluate toughness. Infrared thermography has been employed to follow compressive failure mode developing during an indentation test and a compression after impact test, and to evaluate the fracture toughness of compressive fiber failure. The obtained results show a good correspondence with the value found in a previous work on FE analysis of impact damage and are consistent with the literature.

1. Introduction

The design optimization process of composite structures is classically accelerated by using numerical approach. Finite element analysis (FEA) is extensively elaborated thanks to its ability to precisely simulate particular damage of laminated composites i.e. fiber failure, matrix cracking and delamination. To date, material law regarding fracture mechanics seems to be a reasonable damage model in FEA since it can provide accurate damage results [1–5]. With this approach, fracture energies are required as input parameters for the model. However, these properties can be difficult to determine. Besides, standardized tests have not been established yet [1,6–9]. For standard damage phenomena, such as delamination between plies of a composite laminate plate, the experimental tests are well defined: the DCB (Double Cantilever Beam) test is currently carried out to evaluate fracture toughness in opening failure mode and ENF (End Notched Flexure) is often used to evaluate fracture toughness in shear mode [8–10]. The problem is more difficult for complex damage phenomena, such as compressive fiber failure, for which the crack induces a lot of secondary damage types. Indeed the failure mode of compressive fiber failure in laminated composites [6,7,11,12] is known as a very complex mode, occurring as a result of local buckling of fibers and leading to the kinking process (Fig. 1).

Currently, no standard tests are available to determine the fracture toughness of this phenomenon and the compact compression (CC) test is currently used. Fig. 1c shows a micrographic observation done by Gutkin et al. [12] showing clearly the phenomenon of kink band at the crack tip followed by a phenomenon of crushing. Then to evaluate the fracture toughness of this crack, it is necessary to separate these two phenomena - kink band and crushing. For this purpose, a local approach is needed. This observation is confirmed by Pinho et al. [6] who showed that the zone concerned by the damage in compression is very large, unlike in the case of tension (Fig. 2). The authors conclude "for kink-band formation, propagation values cannot be obtained directly from a stress intensity factor approach because the contact stresses in the faces of the kink cannot be easily accounted for; the area method also failed to produce meaningful results due to kink band broadening and delamination" [6]. Then, local approach is needed to evaluate dissipated energy by compressive fiber failure and the infrared thermography technique may be an answer to this problem.

In this paper, infrared thermography has been used to follow compressive failure mode developed during an indentation test and a compression after impact test, and to evaluate the fracture toughness of compressive fiber failure. From the past 20 years, infrared thermography has been widely used to study the dissipative phenomena in materials, such as plasticity in metals [13,14] or damage in polymers [15]. Using the framework of irreversible thermodynamics, Chrysochoos et al. [16] have presented a methodology to estimate the internal heat sources associated with the

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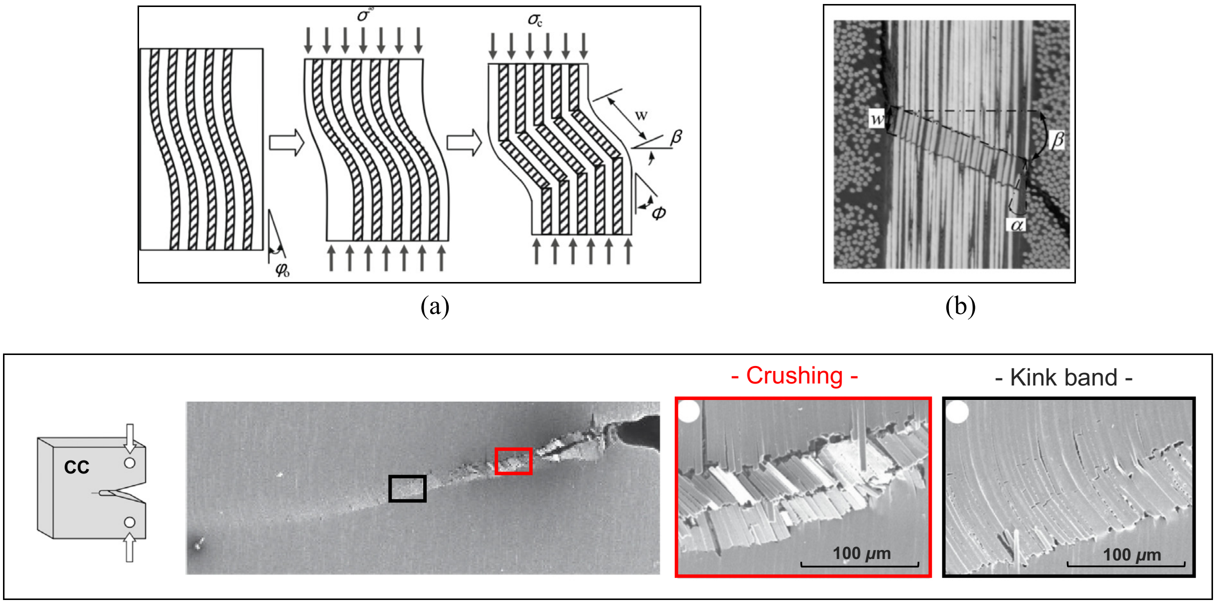
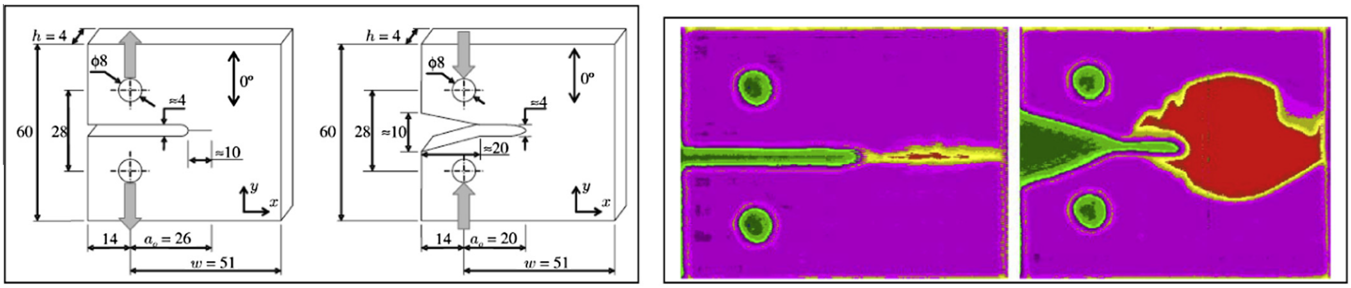


(a) (b)

(c)

Fig. 1. Compressive fiber failure by kinking process: principle [11] (a), micrographic observation [12] (b) and micrographic observation during a CC test [12] (c).



(a) (b)

Fig. 2. Experimental samples of CT (Compact Tension) and CC (Compact Compression), respectively to the left and right of the figure (a) [6] and corresponding ultrasonic observations (b) [6].

dissipative phenomenon from temperature measurement on the sample surface. They show that an estimation of the heat sources makes it possible to locate the damage in time and space and to evaluate the dissipated thermal energy. Nevertheless, the study of dissipated thermal energy by infrared thermography is quite recent in composite materials and is essentially applied to fatigue loading. For example, Naderi et al. [17] used infrared thermography to characterize damage stage evolution by calculating the dissipated heat during fatigue loading of thin woven laminates. They show it is possible to characterize the three characteristic stages of fatigue damage of a woven glass/epoxy using IRT and they compare this technique with acoustic emission. The results of the two non-intrusive techniques show similar response revealing the existence of three degradation stages [17]. Nevertheless, applying crack tip contour integral analysis [18], Freund and Hutchinson [19] and Soumahoro [20] have shown that the fracture toughness is linked to dissipative work. In addition, since the early work of Taylor and Quinney [21], it is well known that dissipative work is mainly converted into heat in metallic [22] and polymeric materials [23]. For example, Kapoor and Nemat-Nasser [22] show the infrared measurement yields more than 70% conversion of work to heat for Taork is mainly converted into heat in metallic [since the early work of Ta. Then for this case, the ratio of dissipative work converted into heat should be close to 100%. For polymeric materials, the problem is more complex. Li and Lambros [23] studied a polymethyl methacrylate (PMMA) and a polycarbonate (PC) at different strain rates (10^{-4}–10^{3} s^{-1}). For PC the ratio of dissipative work converted into heat is between 100% for low strain and 50% for high strain and for PMMA, the brittle nature of the material does not permit to define the ratio.

Hence, in this study we propose to link the fracture toughness to the experimental heat sources [24]. In this way, the fracture toughness can be computed even for experiments where the stiffness variation remains small and for which the standard techniques, such as area or compliance methods, are not relevant. Indeed the main drawback of the standard techniques is to sum the dissipated energy of all the damage types of the sample and as a result to overestimate the value of the fracture toughness. For example for an ENF test, the area method adds the dissipated energy due to propagation of the crack in mode II but also the dissipated energy due to the crushing of the beam under the boundary conditions.

The fiber compressive failure is usually considered as a complex failure mode [6,7,11,12]. Furthermore, the critical energy release rate in compression, G_{Ic}^{comp} (generally referred to mode I intralaminar fracture) is even more complex. Different approaches have been proposed in the literature to determine this value. For